PULSE DETONATION ENGINE AIR INDUCTION SYSTEM ANALYSIS

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Abstract

A preliminary mixed-compression inlet design concept for potential pulse-detonation engine (PDE) powered supersonic aircraft was defined and analyzed. The objectives of this research were to conceptually design and integrate an inlet/PDE propulsion system into a supersonic aircraft, perform time-dependent CFD analysis of the inlet flowfield, and to estimate the installed PDE cycle performance.

The study was baselined to a NASA Mach 5 Waverider study vehicle in which the baseline over/under turboramjet engines were replaced with a single flowpath PDE propulsion system. As much commonality as possible was maintained with the baseline configuration, including the engine location and forebody lines. Modifications were made to the inlet system's external ramp angles and a rotating cowl lip was incorporated to improve off-design inlet operability and performance. Engines were sized to match the baseline vehicle study's ascent trajectory thrust requirement at Mach 1.2. The majority of this study was focused on a flight Mach number of 3.0.

Two generalized concerns were addressed about the operability of non-steady engines operating in the environment of a steady flow inlet. These concerns were (1) as the valving in the PDE's close in guillotine fashion, will it cause a hammershock, which will unstart the inlet and (2) will a given arrangement of PDE's allow the establishment of stable shock system terminating with a normal shock in the inlet throat. A non-steady CFD analysis was initiated to answer these two concerns.

The time-dependent Navier Stokes CFD analyses of a two-dimensional approximation of the inlet was conducted for the Mach 3.0 condition. The LMTAS (Lockheed Martin Tactical Aircraft Systems)-developed FALCON CFD code with a two-equation 'k-l' turbulence model was used. The downstream PDE was simulated by an array of four sonic nozzles (valves) in which the flow areas were rapidly varied in various opening/closing combinations, similar to the operation of multi-duct PDE rotary valves. Results of the CFD study indicated that the inlet design concept operated successfully at the Mach 3.0 condition, satisfying mass capture, total pressure recovery, and operability requirements. Approximately 5.0% inlet bleed was required to stabilize the terminal shock train in the isolator region. Time-dependent analysis indicated that pressure and expansion waves from the simulated valve perturbations did not effect the inlet's operability or performance.

Installed PDE cycle performance analyses were conducted using a LMTAS-developed PDE cycle analysis code at Mach numbers of 1.2 and 3.0. Realistic component performance values were used in the analyses, and ethylene (C_2H_4) was used as the baseline fuel. Calculated effective I_{sp} values were higher for the Waverider design powered with PDE's than with the baseline propulsion system.

INTRODUCTION

The pulse detonation engine (PDE) is being evaluated and developed as a potentially high-payoff new aeronautical propulsion system. The PDE represents a potential propulsion technology leap beyond the gas turbine engine. Based on the results of several studies to date (Refs. 1–4), the airbreathing PDE offers potential performance and life cycle cost payoffs for both subsonic and supersonic vehicle applications. Pulse detonation rockets and hybrid airbreathing/rocket PDE systems are also recognized to offer large potential benefits, especially for missile applications. The maximum operating condition for the pure airbreathing

PDE is projected to be in the Mach 3 range, depending on fuel autoignition constraints. Hybrid pulse detonation systems may have higher Mach number application. Potential applications of interest are propulsion systems for tactical aircraft (manned or unmanned) and missiles and subsonic/supersonic propulsion sources for future hypersonic aircraft.

PDE development is still in a very early development stage with many potential development risks to be faced before operable engines will be a reality. As with any high risk, high potential payoff technology, critical enabling technologies should be identified and addressed early to reduce the risk of encountering show-stopper issues and to accelerate the development of an optimum concept. One of the critical, enabling technologies is the integration of supersonic air induction systems with the intermittent flow PDE cycle. It has been estimated that in order for the PDE cycle to be competitive with conventional turbojet/turboramjet systems, they will be required to operate in the 75 to 100 Hz range with near stoichiometric fuel/air mixtures. This represents a cycle time of approximately 10 msec, requiring a propellant refill time in the 5 msec. range. Developing compatible air induction systems that will satisfy the above requirements, as well as provide adequate sealing from the high pressure, high temperature exhaust products, represents a major technology challenge.

The objective of this study project was to initiate the development of PDE/vehicle integration expertise, especially as related to air induction systems, through the conceptual design, analysis, and integration of a supersonic mixed-compression inlet system that is compatible with the PDE cycle. The approach was as follows:

1. Select or define a notational study vehicle concept that will permit replacement of conventional propulsion systems with PDE systems.

2. Define the vehicle flight requirements and determine propulsive thrust requirements.

3. Define a PDE modular design concept that is compatible with the selected notional vehicle and which can be reasonably sized to satisfy thrust requirements.

4. Define and size an inlet system design concept.

5. Integrate the inlet system and PDE modules into the notional vehicle.

6. Perform steady-state and time-dependent full Navier-Stokes CFD analysis of the inlet at a selected supersonic flight condition for evaluation of inlet performance, inlet operational compatibility with the intermittent flow PDE, and assessment of bleed requirements for terminal shock stabilization.

7. Compute PDE installed performance.

PDE DESIGN AND VEHICLE INTEGRATION

Notional Vehicle Description

The first task of this program was to establish a notional vehicle definition to serve as a baseline for this study. A NASA Waverider study vehicle design concept (Ref. 5) was selected. This 500,000-lb. class (TOGW) vehicle conceptual design, illustrated in Fig. 1, designed for Mach 5 cruise, was powered by four Pratt & Whitney over/under turboramjet engines, which were integrated with the vehicle's lower surface, and fueled with an endothermic hydrocarbon fuel. The decision was made to replace the turboramjet engines with PDE's, thus reducing the dual flow paths with a single flowpath and limit the PDE application to $M_\infty = 3.0$.

Engine Sizing

PDE sizing requirements were based on ascent trajectory aerodynamic drag and thrust histories as presented in Ref. 5. (No additional vehicle performance analysis was conducted during this study.) The vehicle drag and thrust histories from the above reference are shown in Fig. 2. The engines were sized for a Mach 1.2/25,000-ft. flight condition. As indicated in the above figure, at $M_\infty = 1.2$, the total installed turbojet engine net thrust for the vehicle was approximately 90,000 lbs. with a Thrust/Drag ratio of approximately 1.2. Also, the ascent trajectory installed thrust at $M_\infty = 3.0$ (end of turbojet/ramjet transition region) was approximately 120,000 lbs. with a Thrust/Drag ratio of approximately 1.7. For this study, it was assumed the maximum flight Mach number for PDE operation would be 3.0. Stoichiometric fuel/air ratio (equivalence ratio (Ø) = 1.0), near-instantaneous Chapman-Jouguet (C-J)-quality detonation wave generation, and component efficiencies, i.e., inlet ram recovery, η_r, combustion efficiency, η_c, and nozzle gross thrust coefficient (C_{FG}) values were estimated at each flight condition analyzed in the engine sizing study.

PDE Module Design Concepts

Several generalized PDE designs have been patented, two of which are shown in Fig. 3 (Refs. 6 and 7). These designs feature rotary valves for both front and side filling, spark and laser ignition, stratified gas ignition (fuel/oxygen mixture in the immediate ignition point vicinity for quick detonation ignition and fuel-air mixture for the primary detonation wave to burn into) pre-mixed and post-mixed reactants, annulus, cylindrical, and multi cylindrical designs, lubrication and cooling systems, purge air, etc.

This paper assumes a PDE detonation volume and valve areas large enough to support detonation frequencies up to 110 Hz. LMTAS studies have shown that side valve designs provide enough fill area to support frequencies in the 100 Hz range, where the fill area throats are choked. The results of this study are based on a side-loading engine concept. Individual engines are clustered together in modules. For this study three modules, each containing eight engines, were successfully integrated into the propulsion system envelope of the Waverider. This is shown in Fig. 4.

PDE/Vehicle Integration

The intermittent combustion process is the most unique feature of the PDE that effects integration. This intermittent process is composed of essentially three phases, i.e., (1) a filling phase in which fuel and oxidizer are injected into the duct and are mixed (if not pre-mixed), (2) the detonation phase in which the propellants are ignited and a resulting high pressure detonation wave formed which traverses the length of the duct and exits through the exhaust system, and (3) a blowdown phase in which the products of combustion are pumped out the duct's exhaust system. Positive axial thrust is produced in phases 2 and 3. In order to reduce the impact of intermittent combustion on the air induction system, it is necessary for the PDE module to be made of a group, or cluster, of pulse detonation ducts that operate out of phase such that the airflow rate in the PDE module's common inlet duct is relatively constant.

Inlet Duct Design

The turboramjet air induction system for the study vehicle is a two-dimensional, mixed compression inlet design with the vehicle forebody providing precompression and a boundary-layer diverter provided at the beginning of the first inlet ramp. Inlet strakes (internal splitters) are provided to isolate the four turboramjet flowpaths in case of an inlet unstart, and variable geometry is provided through variable ramps on the body side.

A major challenge of this study was to design a relatively short isolator and diffuser to satisfy the selected "most challenging" PDE modular integration, i.e., the two wide by four high engine module. This requires a two-dimensional duct height change from the 12.5-inch-high isolator to the approximately 75-inch-high engine face in a relatively short distance (approximately 180 inches). In order to allow as much length as possible for the diffuser, a decision was made to retain the baseline vehicle's forebody boundary-layer diverter and to use an aggressively short isolator length, i.e., a length-to-duct height ratio of only 4.0 and to depend on throat bleed to stabilize the terminal shock system (shock trap) in the isolator. This leaves 130 inches for the approximately six-to-one area ratio diffuser. To obtain this aggressive diffusion rate with a reasonable area distribution and acceptable local flow angles requires a diffuser center body and a plenum section just forward of the engine face. Although the center body adds weight to the inlet system, its volume can be used advantageously for O_2 storage and/or PDE valve drive or ignition system hardware. The area distribution is shown in Fig. 5. Note that a rapid local area increase (plenum) is provided aft of the center body, after the inlet airflow has been diffused to an appropriately low Mach number (≈ 0.2). The plenum, in addition to further reducing the airflow Mach number at the engine face, prevents pressure pulses and expansion waves caused by individual PDE valve activity from feeding upstream and disturbing the terminal shock system. Also note that the area distribution from the isolator exit to the maximum height of the center body is near-identical to the area distribution of a conventional equivalent 5.5° (half angle) conical diffuser and that no severe local flow angles are encountered prior to the plenum section. A schematic of the inlet is shown in Fig. 6.

INLET TIME-DEPENDENT CFD ANALYSIS

Full Navier-Stokes analysis was used to evaluate a 2-D approximation of the inlet isolator/diffuser design at the Mach 3.0/50,000-ft. flight condition. The CFD code used was a LMTAS-developed 2-D, first-order, time-accurate central difference finite-volume code (CD FALCON) (Ref. 8) using the LMTAS-developed 'k-l' two-equation turbulence model (Ref. 9). The turbulence model is structured with wall functions, which allows y+ values to be greater than unity at the wall. The grid was generated using GRIDGEN 10. Both steady state and time-accurate unsteady analyses were conducted to evaluate the effects of the PDE multi-valve flow area variations on the operation dynamics of the inlet airflow characteristics. The time-dependent solutions were run at physical time steps of 0.24 microseconds per iteration. If strong pressure perturbations, such as hammershocks develop as the PDE valves close, a fine time resolution is required to trace the development and propagation of the wave. One of the principle investigations of this study was to determine if a hammershock of sufficient strength is formed, which will propagate upstream to the terminal normal shock in the constant area isolator, and unstart the inlet.

Time-dependent CFD analysis was performed on the internal inlet system from the cowl lip plane to the engine face. The starting condition included pre-compression from the forebody and external ramps. It was assumed that the boundary-layer diverter of the baseline vehicle removed all of the forebody boundary layer. The boundary layer developed on the external inlet ramps was assumed to be bled off at the cowl lip place (approximately 1.5% of inlet captured mass flow estimated). The engine face consists of four simulated rotary valves, which open and close to intermittently ingest air for the pulse detonation cycle. Typical cycle times are approximately 10 to 16 msec. The fill time represents roughly 4 to 5 msec. (nominally 1/3 of the PDE cycle time). These valves were represented as nozzles with choked throats whose area controls the amounts of flow going through the nozzle. When the flow is sonic at the throat (choked flow), the mass flow can be reduced when the throat area is reduced. When flow transfers between PDE valves (when one is opening, the other is closing) are considered in terms of tens of microseconds, the static and total pressure does not have time to vary significantly. Therefore, the pressure is assumed to remain essentially constant during the flow transfer between valves. Thus, by varying the area of the valves, flow through the valves will be controlled in the CFD analysis. Since the valves will be run out of phase, a natural sequence of events will supply the prescribed opening and closing schedules.

Figure 7 shows the detailed grid used in the analysis, consisting of 236 longitudinal points and 105 lateral points. A center body is included in the highly divergent duct, as well as four valve throats at the end of the duct which represent a bank of engines. The center body does not extend all the way back to the engine face, where a large gap (plenum) is provided to transfer flow when valves are shut down and opened up. Flow transfer studies included flow between adjacent valves as well as some cases where the flow transfer length was up to two engine diameters away. Thus, a sizable plenum gap was used to ensure adequate transfer time for the worst case situation.

The valve throat areas must be initially sized in order to set a back pressure sufficient to set the terminal shock in the constant area isolator duct. The required total (cumulative) valve throat height was found to be approximately between 11 and 12 inches, depending on the viscous effects. The throat height in Fig. 7 is 11.3 inches and the isolator duct heights is 12.5 inches, as determined in the inlet sizing study for the Mach 3.0/50,000-ft. flight condition. This approximation sets the terminal shock approximately half way down the isolator duct. A shock trap is set by bleeding top and bottom areas just upstream of the terminal shock. The isolator bleed was set for approximately 3.5% of the flow entering the inlet (for a total of approximately 5.0% bleed which includes inlet ramp bleed at the cowl lip plane). This bleed rate was sufficient to hold the terminal shock and not allow it to propagate upstream for any intermittent condition that was applied to the valves in their various sequencing patterns.

The initial conditions at the internal inlet were generated by an inviscid analysis using FALCON where the ramps prior to the inlet were included. This is shown in Fig. 8. With this starting solution applied to the grid in Fig. 7, a solution was obtained for the steady state mode. Then allowing valves 1 and 4 (see Fig. 7) to remain constant at 0.562 slugs/sec. and 0.99 slugs/sec., respectively, and changing valve 2 from 0.861 slugs/sec. to 0.36 slugs/sec. and valve 3 for 0.823 slugs/sec. to 1.6 slugs/sec. instantaneously, the flow transfer was closely monitored by the finely spaced time-dependent CFD analysis. Figure 9 also shows the flow drop in valve 2 to be almost instantaneous, whereas the flow in valve 3 has a more gradual buildup. The transfer was so rapid that there was no possibility that a hammer shock could form.

From Ref. 10, this requires approximately 12 msec. The distance from throat 2 to throat 3 was 65 inches, where Fig. 9 shows the bulk of the flow transfer taking place in approximately .007 msec. and a flow balance to be reached in 1.0 msec. at 17000 iterations. From 13420 iterations to 14000 iterations, flow going out of the valves is slightly greater than flow coming in the inlet. Figure 10 shows velocity vectors colored by Mach number just after the switch over, where the flow is supplied to valve 2 on the back side of the center body. Figure 11 shows the total stagnation pressure, referenced to the incoming inlet flow, which averages approximately 70%. (A total pressure recovery, η_r, of 65% was assumed in the baseline installed performance analysis at this condition.) Static pressure at iteration 17000 shows relative static pressures in the duct and illustrates that constant pressure boundary conditions would be difficult to implement at the diffuser exit. The flow transfer length from valves 2 to 3 was the longest and represents the worst case. Flow transfer lengths from valves 1 and 2 or 3 and 4 are approximately 50 inches from throat to throat. Similar CFD analyses were performed on valves 1 and 2 with 3 and 4 held constant, where similar time-dependent results regarding flow transfer times were obtained.

The analytically demonstrated stable operation of the simulated inlet/PDE system for the selected "worst-case" integration concept is very encouraging. It should also be noted that 2-D CFD simulation of this is more severe than for the actual integrated inlet/PDE geometry since it does not permit 3-D relaxation of pressure pulses.

INSTALLED PERFORMANCE

Another important task of this study was to estimate installed engine performance for the PDE. In order to accomplish this task, an understanding of the PDE cycle, an acceptable cycle analysis code, and realistic estimates of inlet, combustor, and nozzle efficiencies are required.

Cycle Analysis Procedure

Detonation in the PDE is a form of combustion that differs significantly from deflagration, the type of combustion found in conventional gas turbine engines, pulse jets, and rockets. Deflagration is characterized by subsonic wave speeds, whereas the detonation combustion process occurs at high supersonic wave speeds relative to the unburned reactants (approximating C-J conditions). Detonation engines take advantage of this supersonic wave speed to produce a cycle of extremely short duration (about 10 msec.) which allows frequencies on the order of 100 Hz. The detonation acts as an aerodynamic piston as it travels through the reactant gas mixture, raising the useable pressure by a factor of 7 to 8. This constant volume combustion process is thermodynamically more efficient than the constant pressure deflagration combustion process and provides greater available energy for performing useful work.

To describe the entire PDE cycle requires not only modeling detonation waves, but also the complex rarefaction waves. Utilizing both the detonation jump conditions and the expansion wave relationship which consist of the characteristic Riemann invariant time integration relationships, a time-dependent thermodynamic cycle has been defined. For the case with ignition near the thrust wall, the following primary cycle events are illustrated in Fig. 12:

1. Combustion chamber (detonation duct) is filled with detonable fuel/oxidizer mixture.

2. Detonation is initiated near the thrust wall (closed end of duct) and near C-J-quality detonation wave propagates through the duct.

3. Detonation wave exits the duct. The duct is filled with burned gases at pressure and temperature levels considerably higher than ambient conditions.

4. The burned gases exit the duct in a blowdown process as rarefaction waves propagate forward from the open end of the duct.

5. The rarefaction eaves, after being reflected off the closed end (thrust wall), exit the duct after most of the burned gases have been exhausted.

6. After the reflected rarefaction waves have been exhausted, the duct is at a near uniform low pressure level and ready for the purge of the remaining burned gases and subsequent refill of detonable fuel-oxidizer mixture; thus, beginning a new cycle.

Previous research has provided sufficient understanding of detonation and rarefaction physics to describe the PDE cycle and to develop an approximate algebraic, 1-D cycle analysis code which compares favorably with CFD (Ref. 1). The cycle analysis code models planar detonations in tubes with a thrust wall and ignition initiation specified anywhere in the tube. A parametric engine performance model was developed by LMTAS for PDE-powered vehicle analysis studies.

The model provides the user with options to configure a PDE by selecting cycle design parameters in a convenient namelist input format and then generate installed engine performance at selected flight conditions (Mach, altitude, and ambient temperature) and power setting (detonation frequency). The primary unique feature of the PDE cycle analysis model is the detonator solver subroutine. The detonator solver subroutine analytically models the physics of C-J detonation waves and characteristic Riemann waves (see Ref. 1 for more detail). An exhaust nozzle system, which provides additional thrust, can be selected. The cycle output data format has been developed for analysis convenience, especially for parametric and systems analysis studies. The primary benefit of this cycle analysis code is that it provides rapid, low-cost performance predictions, which are needed for analytical studies, such as this program, and for evaluating large matrices of configurations, flight conditions, etc. for system-level studies.

To demonstrate the validity of the cycle code, its results have been compared with results from the MOZART 1-D CFD code (Ref. 11) (with a complex chemical kinetics model). The time-dependent solutions were in good agreement as indicated in Fig. 13. This agreement between two independently developed analysis tools provide confidence that the PDE cycle analysis code adequately describes the pressure, temperature, and mass flow versus time over the entire cycle. From these basic relationships, time-averaged thrust was computed with both the cycle deck and CFD code. Thrust comparison between the two codes agreed to within 1.5%. Additional information on the cycle analysis code can be found in Refs. 1, 2 and 3.

Baseline cycle performance was computed assuming development of instantaneous C-J detonation waves at the beginning of the detonation tube in a stoichiometric fuel/air mixture. (In reality, oxygen enrichment may be required in the immediate vicinity of the ignition source to obtain a primary detonation. The primary detonation wave will then detonate the stoichiometric fuel/air mixture in the remainder of the tube. Another approach would be to use a high power/high frequency ignitor system.)

Cycle Performance Predictions

Until such time as actual pulse detonation engines are on test stands, calculated performance numbers are only estimates. However, in an effort to address realistic performance, the fill valve coefficients have been estimated at 80% and realistic component efficiencies have been used. The airflow is also assumed to be injected through choked flow rotary valves into the combustion chamber. Frequencies in the 70–100 Hz range are also assumed to be possible. (An engine design study estimates that these frequencies are possible, but are at the upper end of possible frequencies for annular designs.) Based on these assumptions, performance numbers have been generated for Mach/altitude flight conditions of 1.2/25,000 ft. and 3.0/50,000 ft. (see Fig. 14). This first order analysis shows that thrust varies linearly with frequency with the detonation volume fixed. As indicated from Fig. 14a, the required net thrust at Mach 1.2/25,000 ft. is 30,000 lbs. per module or 90,000 lb. total for 3 modules at a frequency of 90 Hz. Figures 14b and 14c also show the fuel flow and inlet airflow for these conditions. For the Mach 3.0/50,000 ft. condition, the engine produced the required thrust at 74 Hz. The fuel-air ratio is stoichiometric. In addition, the net thrust numbers represent thrust generated by expanding the flow to atmospheric conditions and multiplying that number by a CFG correction factor.

CONCLUSIONS

- The NASA Mach 5 Waverider vehicle, with well-defined mixed-compression inlet lines for a turboramjet propulsion system, represents a good baseline vehicle for incorporation of PDE systems for supersonic applications.

- Based on ascent trajectory thrust and drag histories from Ref. 5, the required installed net thrust for the Mach 1.2/25,000-ft. flight condition is ≈ 90,000 lbs. For the Mach 3.0/50,000-ft. condition, ≈ 120,000 lbs. of net thrust is required. The PDE system was sized to satisfy the more demanding Mach 1.2/25,000-ft. condition.

- PDE thrust is a direct function of engine volume and operational frequency. For propulsion systems necessary to power vehicles such as evaluated in this study, operational frequencies on the order of 75 to 100 Hz are required.

- The inlet isolator/diffuser conceptual design integrated well with a three module, four-duct-high PDE concept. A single vehicle inlet duct supplies air to all three PDE modules, with flow splitters between modules. The isolator's length-to-height ratio at the Mach 3.0 flight condition is 4.0. A shock trap boundary-layer bleed system is used to help stabilize the terminal shock train. The short length diffuser's area ratio (also height ratio) is six-to-one. A major feature of the diffuser is a center body which allows a conservative area distribution and acceptable flow angles. The diffuser also includes a plenum aft of the center body, just forward of the engine face, to dampen engine-induced pressure waves.

- Time-dependent, fully viscous CFD analysis results indicate that a terminal shock train can be stabilized in the isolator at the Mach 3.0 flight condition with a reasonable amount of isolator boundary-layer bleed (shock trap) and realistic PDE valve-choked flow areas. Pressure perturbations and expansion waves caused by simulated PDE valve area changes do not disturb the terminal shock system, thus analytically validating the inlet design/integration concept. Computed internal inlet stagnation pressure recovery was approximately 70%, in agreement with previous estimates.

- The CFD analysis results show that for open plenum designs, the transfer of flow between side-valve PDE ducts due to phased valve timing occurs within tens of microseconds. This does not allow time for the formation of potentially destabilizing hammershocks. (Typical times for hammershocks formation is approximately 10 milliseconds.)

ACKNOWLEDGMENTS

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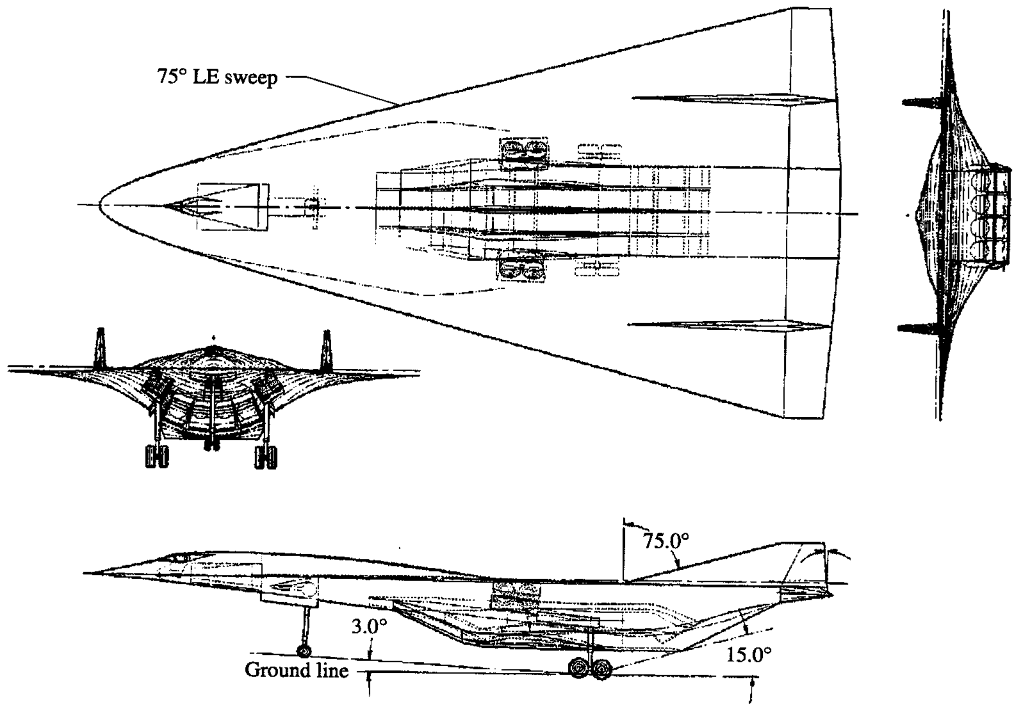


Fig. 1. Notational baseline vehicle (ref. 5).

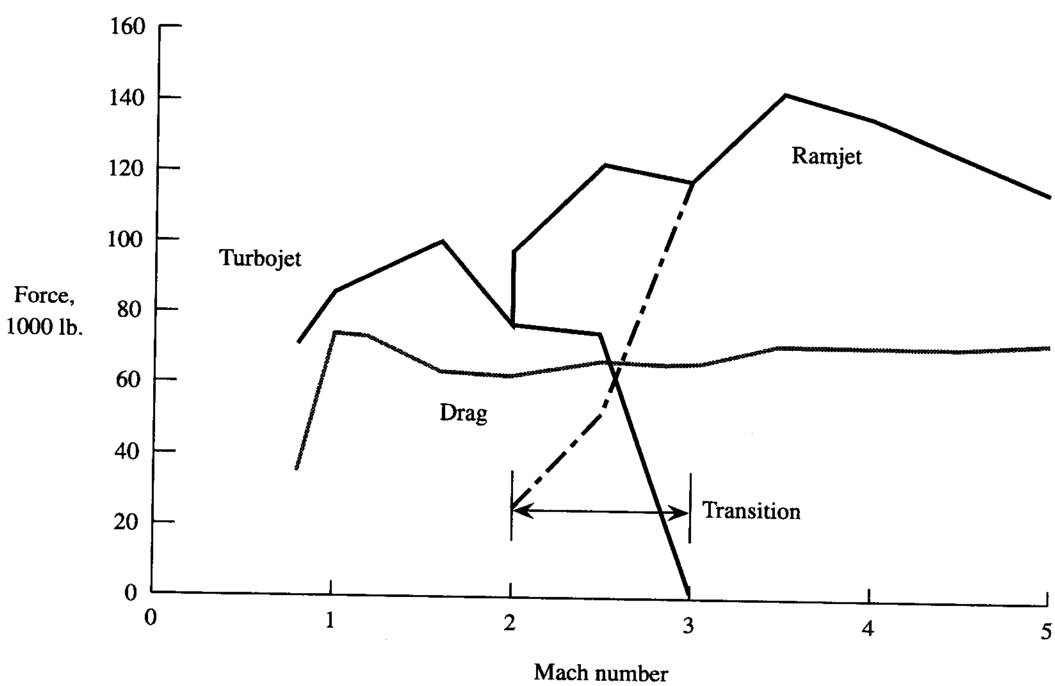
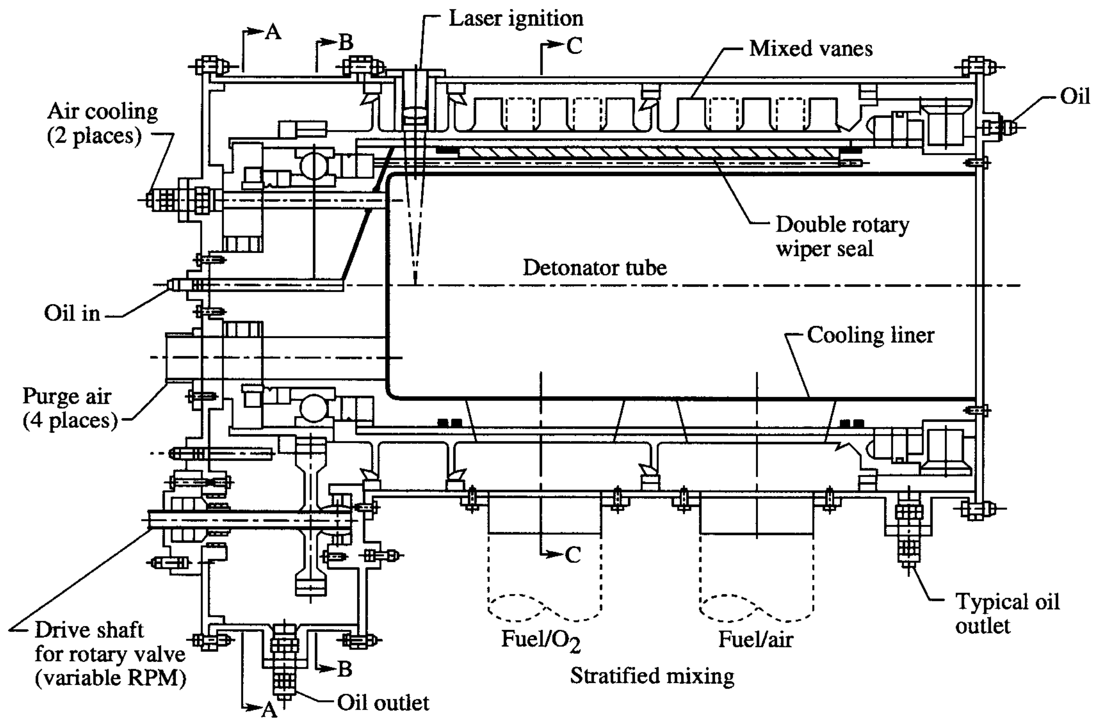
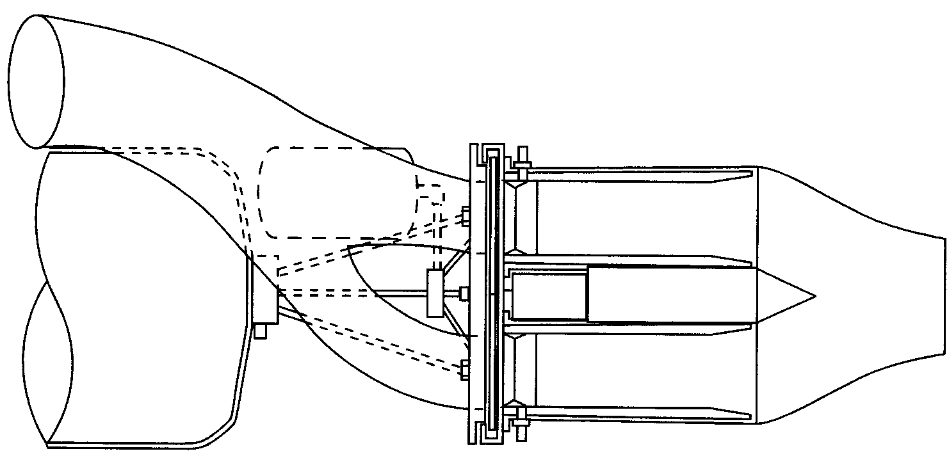


Fig. 2. Baseline vehicle ascent thrust and drag histories.

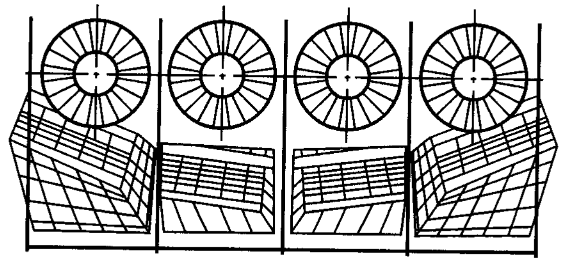


(a) Side loading (U.S. Patent 5,473,885).

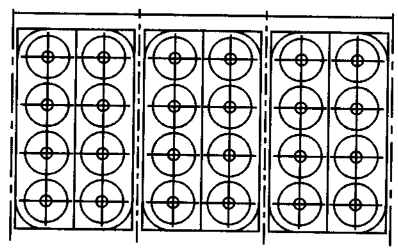


(b) Front loading (U.S. Patent 5,345,758).

Fig. 3. Two types of PDE concepts.



(a) Basic over/under turboramjet.



(b) 3 4×2 PDE modules.

Fig. 4. Engine arrangements in aircraft.

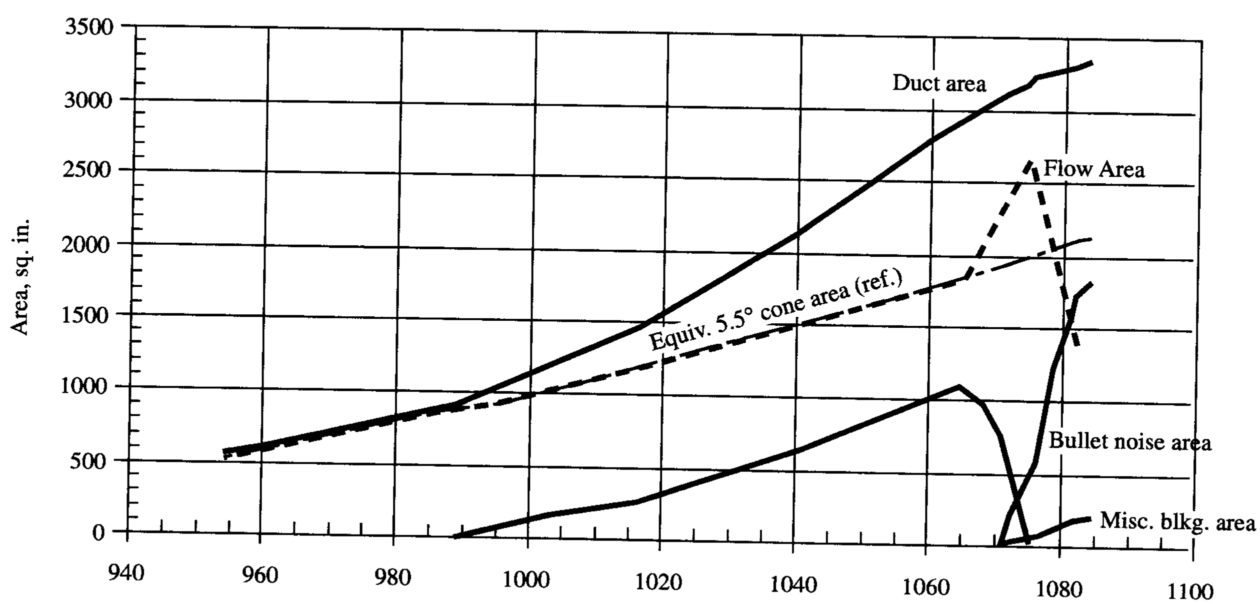


Fig. 5. Inlet diffuser area distribution.

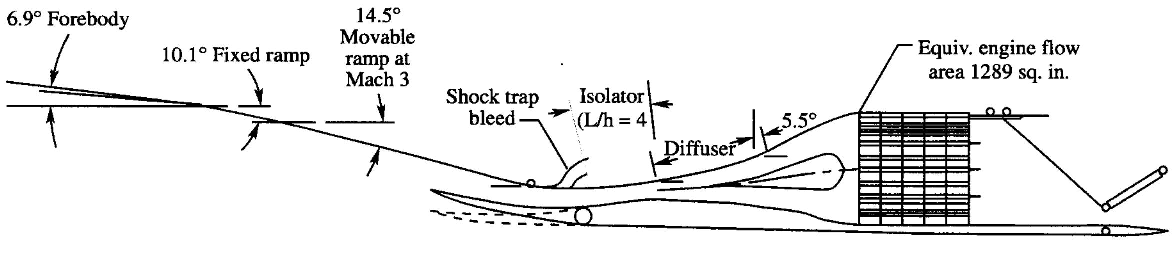


Fig. 6. Inlet geometry.

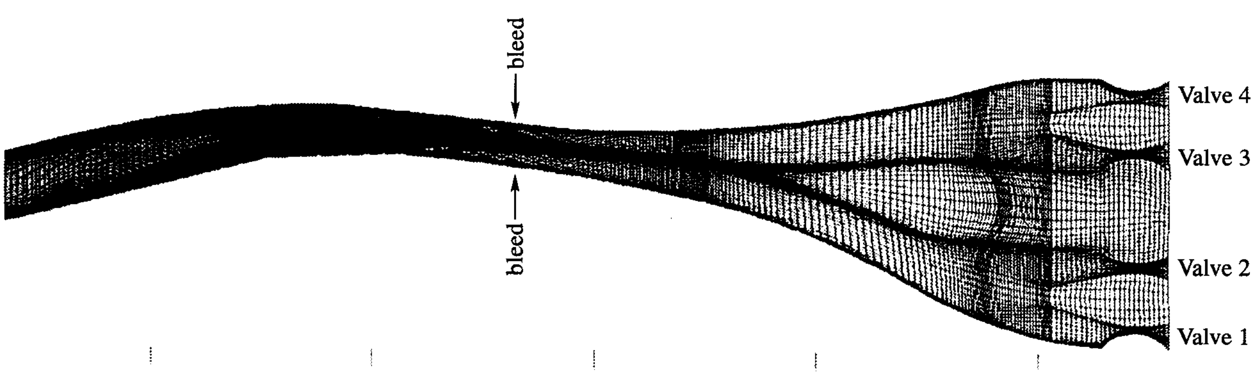


Fig. 7. Grid for detailed inlet CFD valve closure study.

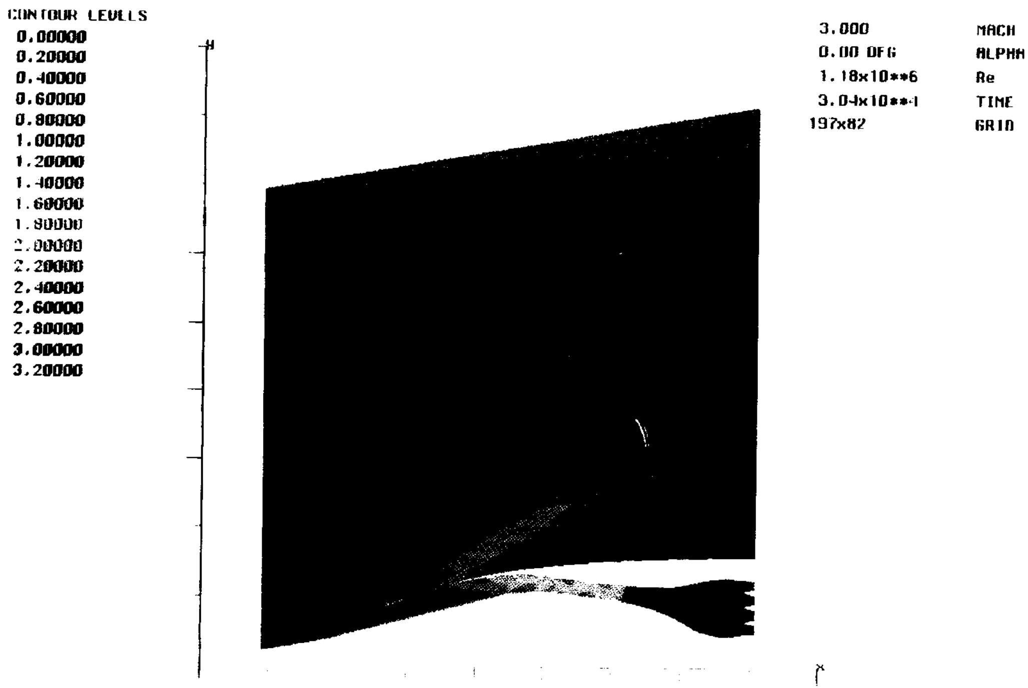


Fig. 8. External/internal Euler flow field solution at M = 3.

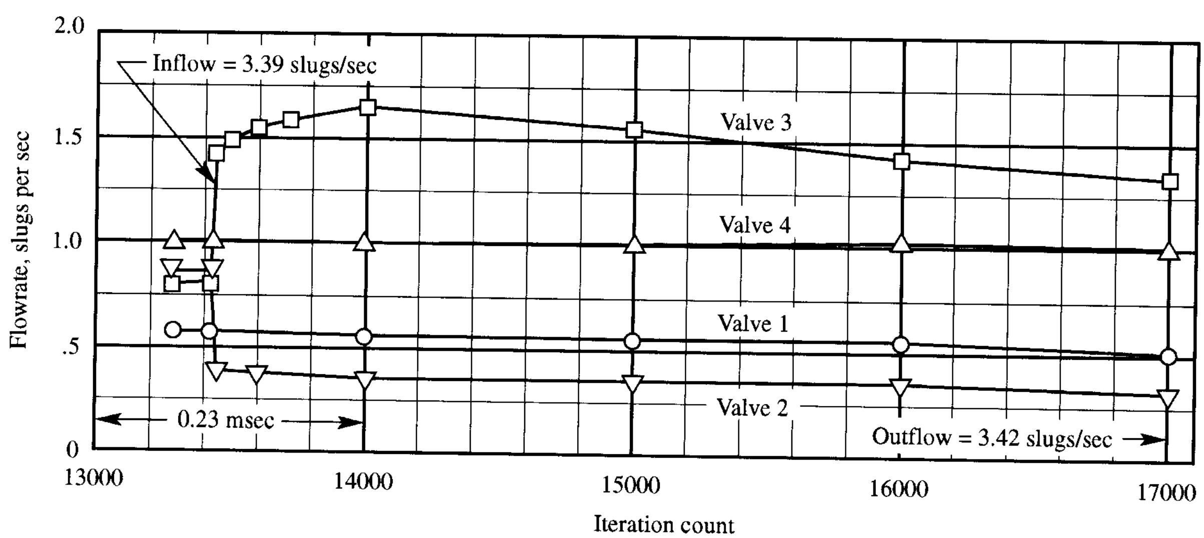


Fig. 9. Valve flow transfer time history.

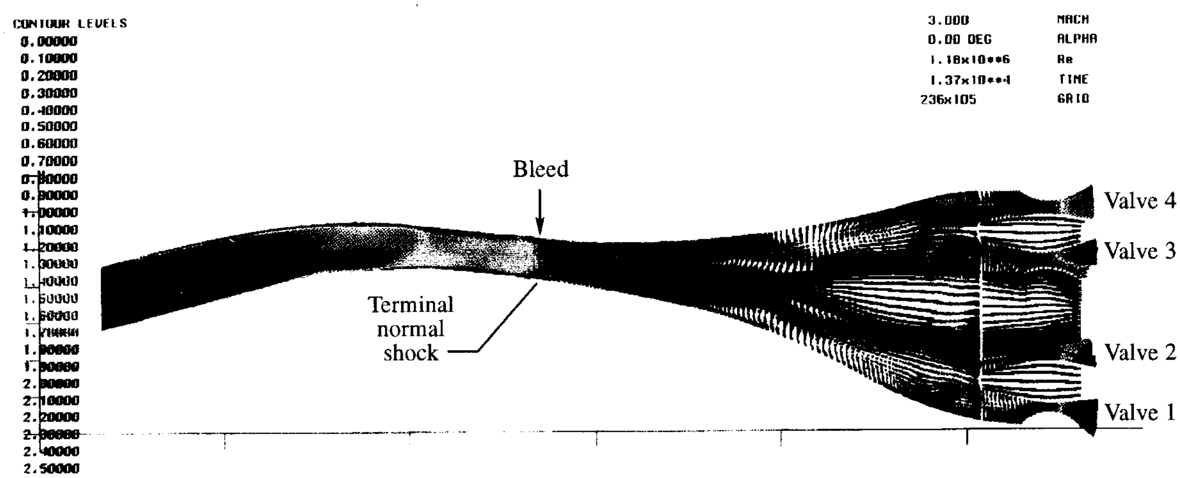
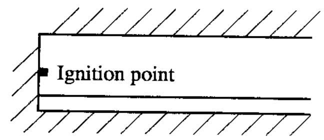
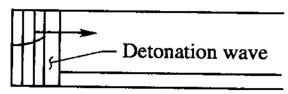


Fig. 10. Velocity vectors just after valves are sequenced (closing valve 2, opening valve 3).

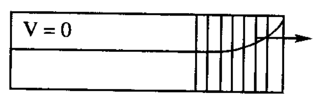
Fig. 11. Total pressure for the case shown in fig. 10.



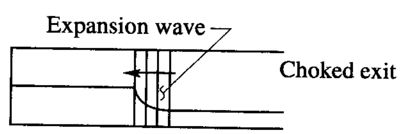
(a) Initial condition.



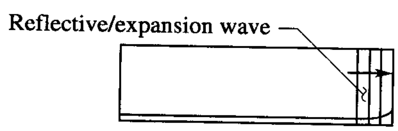
(b) Ignition.



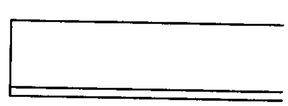
(c) Charge exits chamber.



(d) Steady exit conditions.



(e) Drop in exit mass flow.



(f) Refill.

Fig. 12. Stages of the Pulse Detonation Cycle.

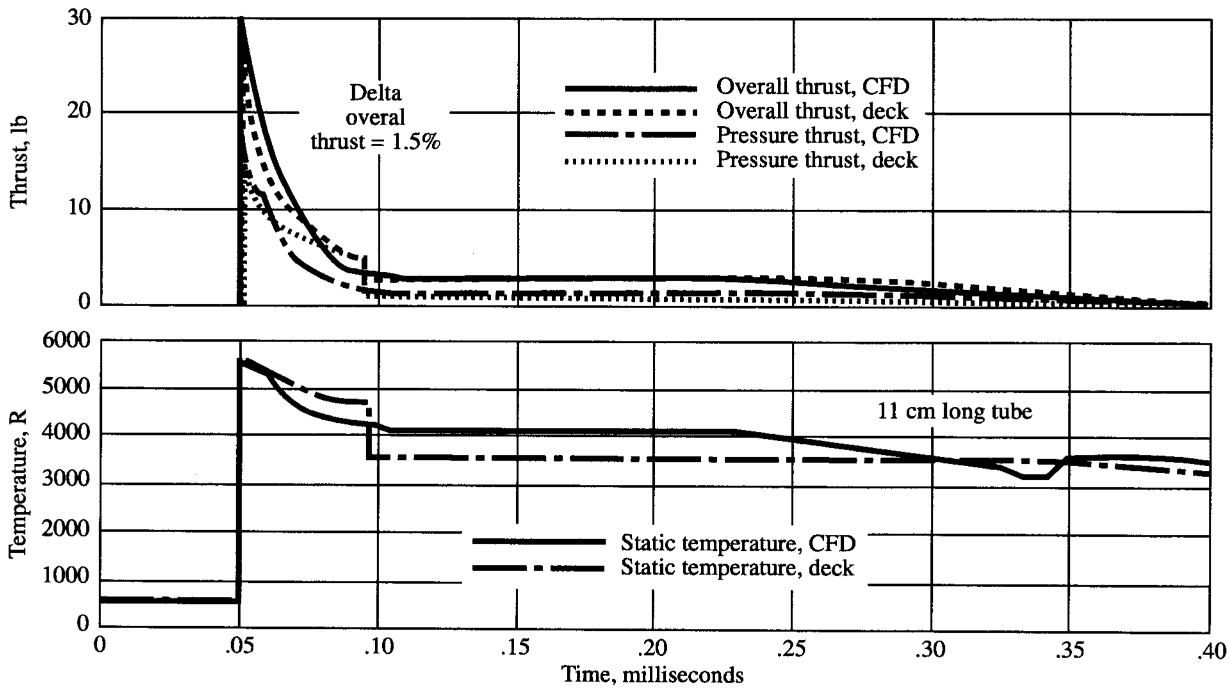
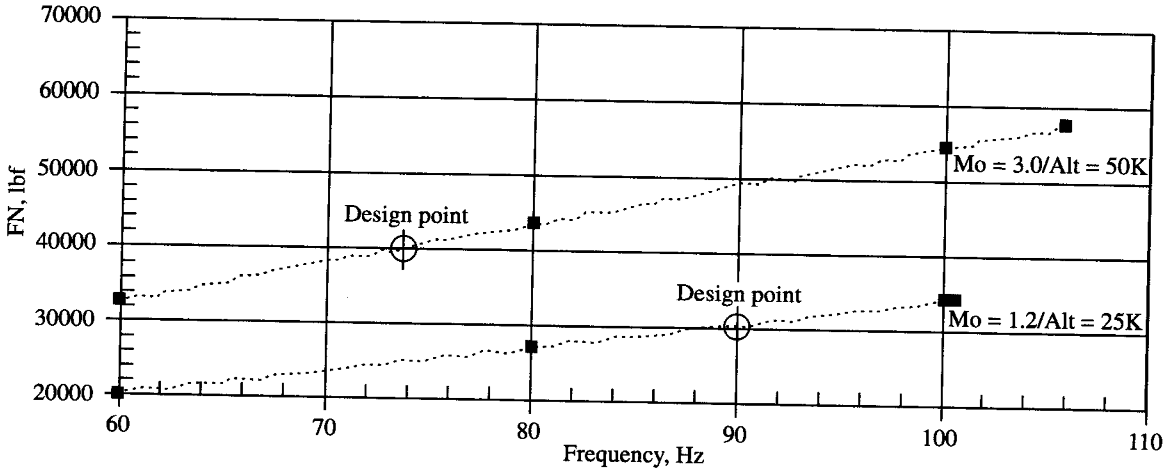
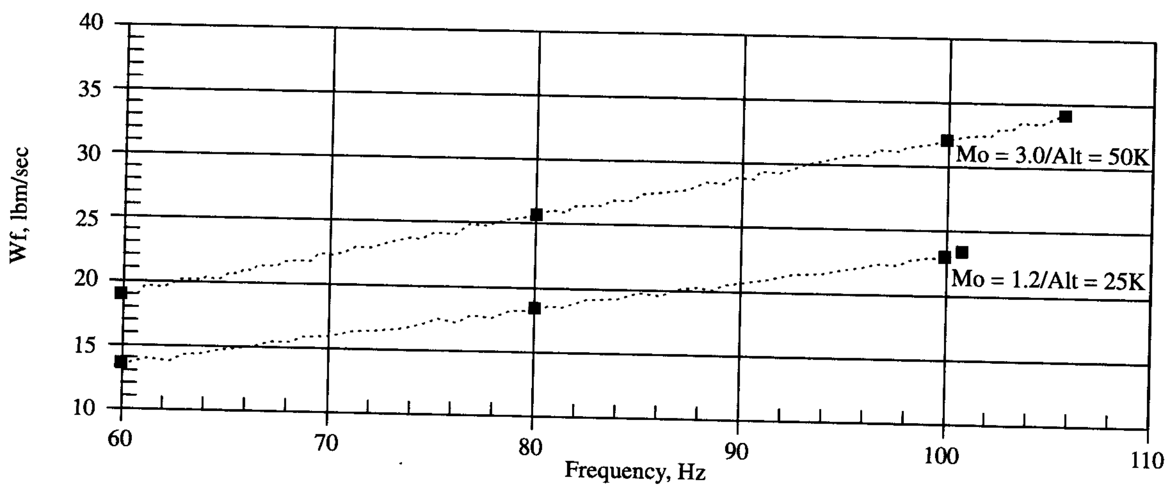


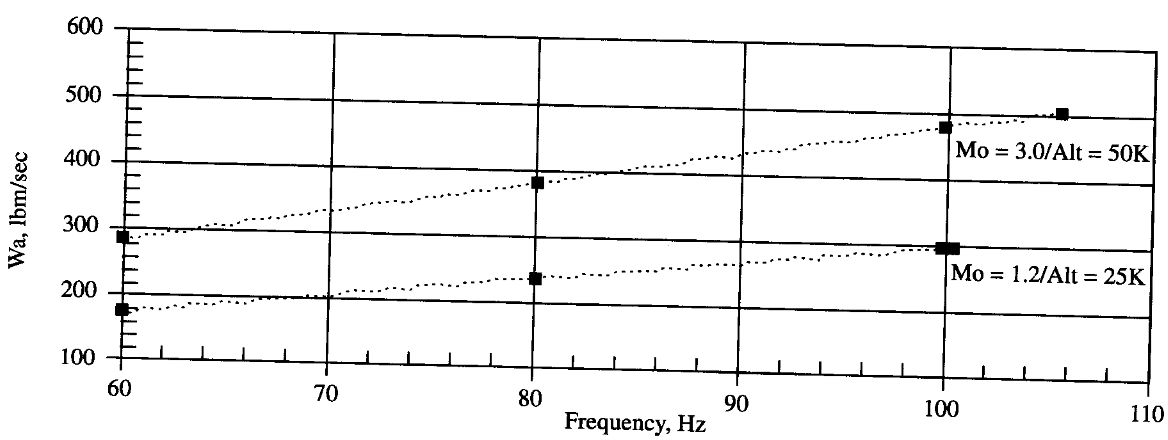
Fig. 13. Comparison of the LMTAS PDE cycle analysis with the 1-D CFD analysis of ref. 11.



(a) Net thrust.



(b) Airflow.



(c) Fuel flow.

Fig. 14. Installed PDE performance parameters for one module.